Analysis & Simulation of an Advanced Inertial Stabilization Concept

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ABSTRACT

The Internal Bearing Stabilized Sighting Unit (IBSSU) is an innovative concept in precision stabilization for high resolution electro-optical sensors mounted in high disturbance vehicle environments. It is an inertially stabilized platform supported by "soft mount" isolators to reduce the effects of vehicle vibration and gunfire on the performance of the sensors. The unit was analyzed and a simulation program written to aid in the evaluation of this advanced inertial stabilization concept. IBSSU is described and the equations of motion showing the coupling between translational and angular motion are listed. The simulation program is used to compute the platform response to disturbance inputs. IBSSU laboratory test data are used to validate the model.

INTRODUCTION

Stabilized platforms containing high acuity electro-optical sensors are used to acquire and designate targets for engagement with anti-tank missiles. A high degree of precision is required since the platforms are mounted in a dynamic environment such as a helicopter or tracked vehicle and must provide sufficient inertial stabilization to prevent the vehicle vibration environment from degrading sensor performance. The stabilized platform described herein is referred to as the Internal Bearing Stabilized Sighting Unit (IBSSU). It was developed by McDonnell Douglas Corporation (1) to introduce passive isolation into stabilized gimbal platforms. It has excellent potential for improving precision line-of-sight stabilization to extend target acquisition and laser designation stand-off ranges for tactical airborne missile fire control.

The IBSSU concept employs "soft mounted" gimbals to provide passive isolation of electro-optical sensors from translational vibrations under normal helicopter operation as well as achieving high rejection of the more severe disturbances caused by on board gunfire. Several critical technologies were involved in the IBSSU development. One was the design of the "super-ball" bearing to support the sensor payload, with the bearing housing suspended on six degree of freedom, low frequency, spring/damper isolators. Due to the relatively large motion of the "floating" platform, it was necessary to develop wide-gap torquers. These actuators operate on the i(1XB) principles and employ a samarium cobalt permanent magnet. The design is such that the torques produced in each axis are independent and always aligned with the axis.

Figure 1 is a schematic of the mechanical components. Figure 2 and 3 contain plots of the specified input translational and angular vibrations. The control loops are shown in Figures 4 and 5. The gyro loops are critical to the stabilization of the payload. The payload can be positioned in angle with respect to the aircraft in azimuth and elevation, but follow the aircraft in the roll axis.

Stabilization of the platform when subjected to disturbances is the critical performance measure. This stabilization is only slightly affected by relative angular position of the components; thus to simplify the equations, the axis of the vehicle and mechanical components of IBSSU are assumed to be aligned. Small angle approximations are used to take into consideration coupling of the equations for each axis. Because of the mechanical layout, it is likely that there will be some mass unbalance. Mass unbalance will result in coupling between the angular and translational equations of motion. These effects are included in the equations. Since the platform "floats", it is not sensitive to gear back lash and that phenomena is not included in the equations.

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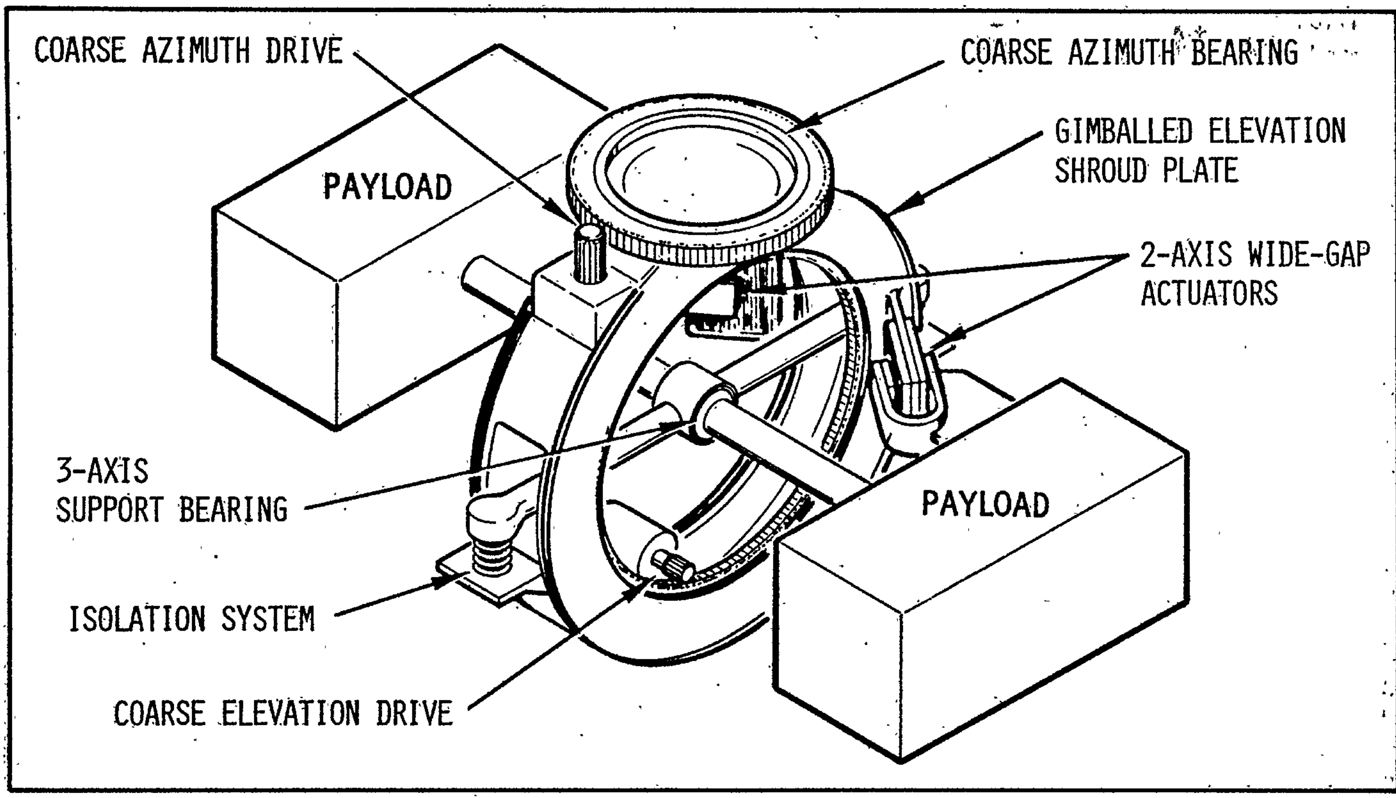

Figure 1. Schematic of IBSSU Components

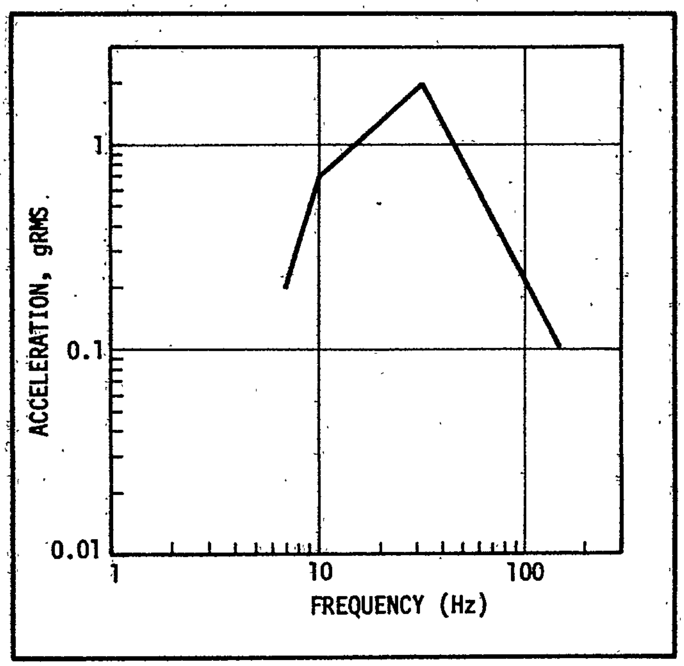

Figure 2. 3-Axis Translational Disturbance

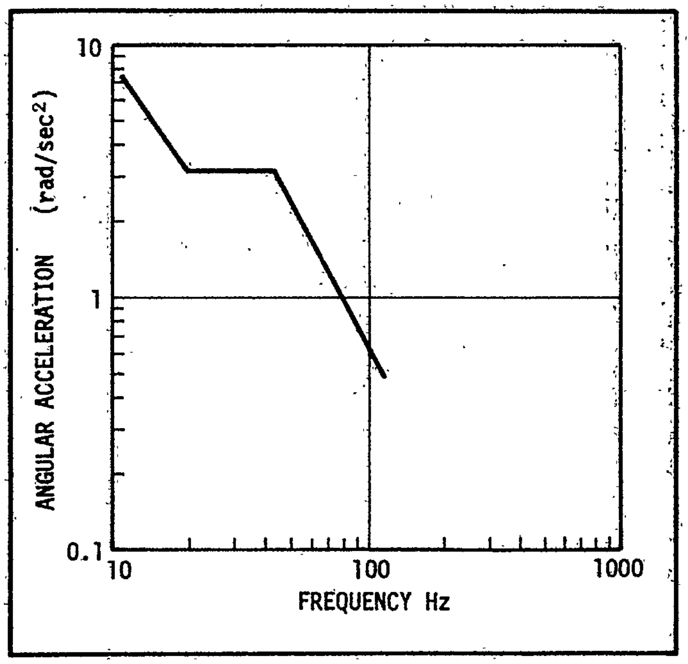

Figure 3. 3-Axis Angular Disturbance

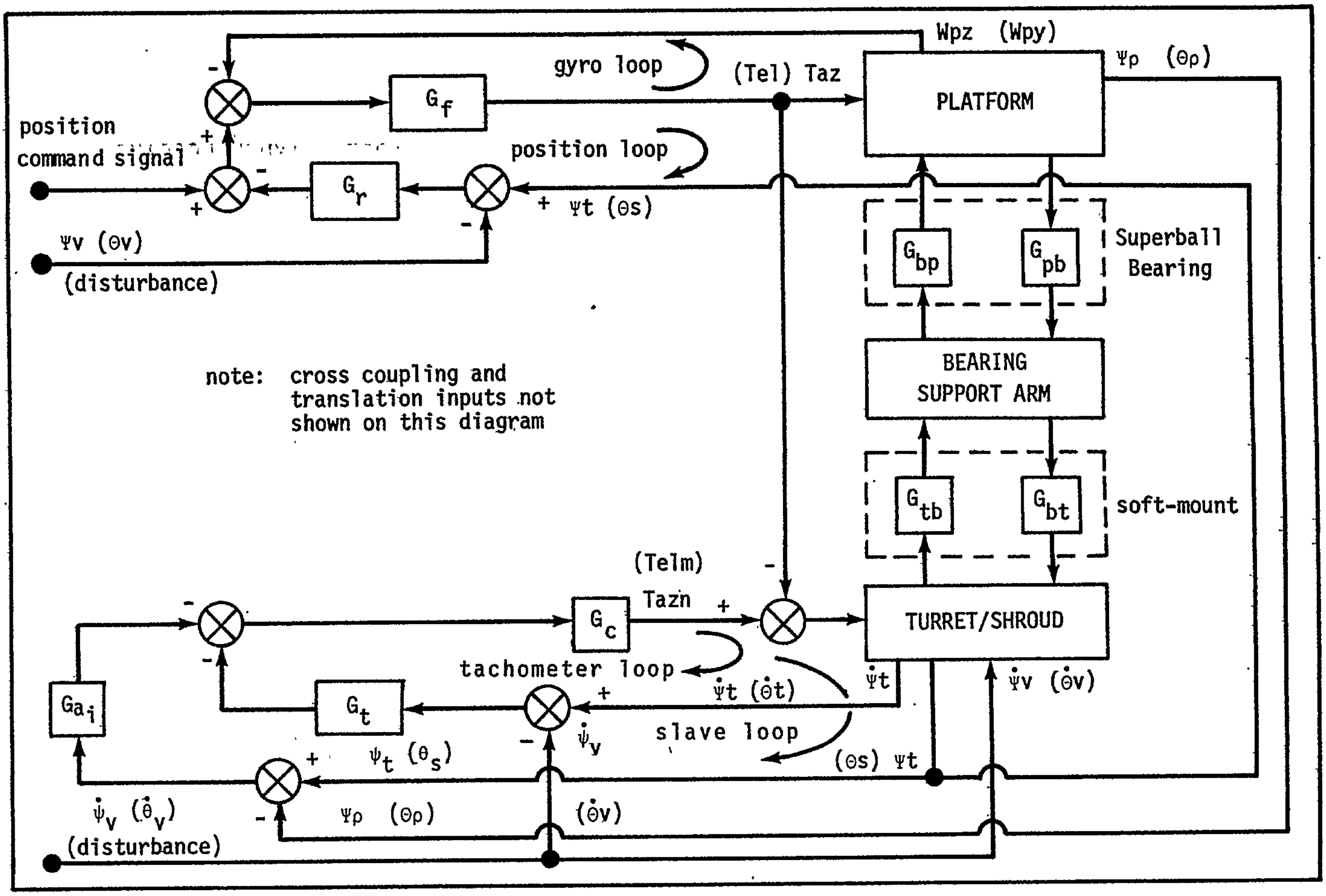

Figure 4. Elevation and Azimuth Axis Control Loops

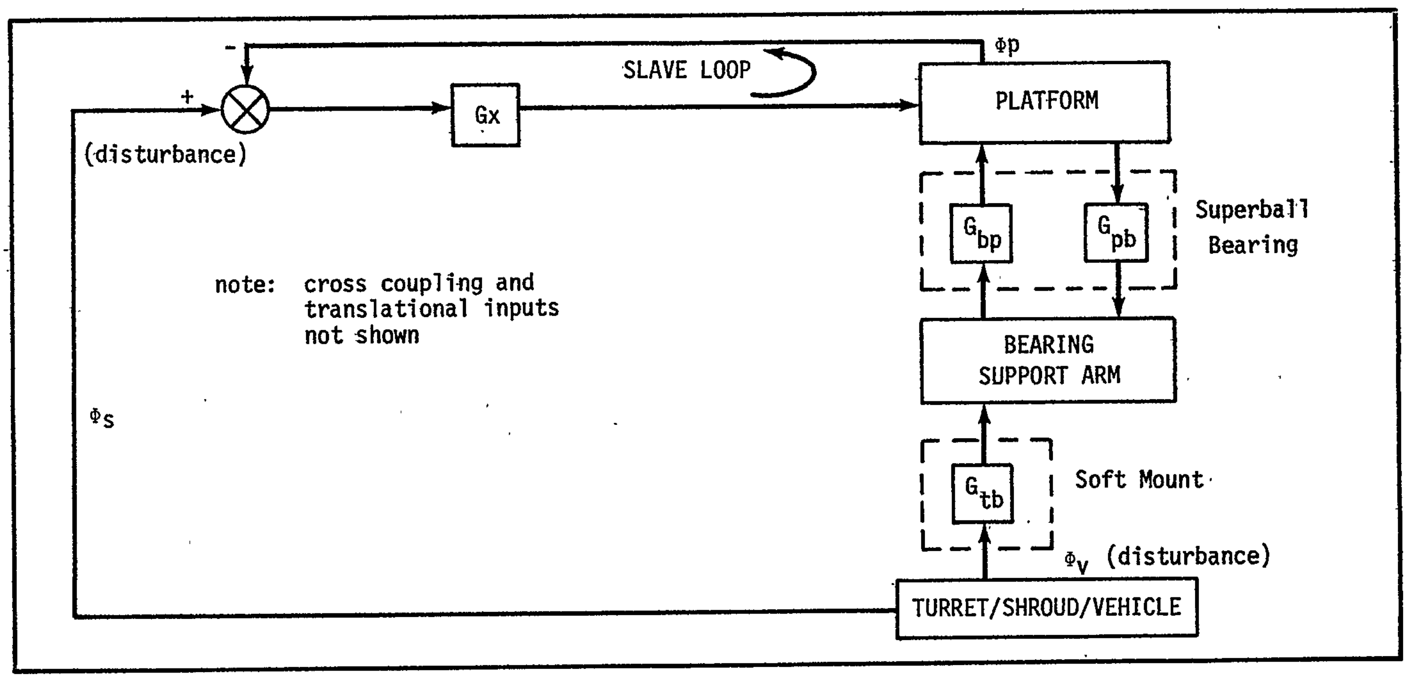

Figure 5, Roll Axis Control Loop

EQUATIONS OF MOTION

This section contains the equations of motion (2, 3) for the four mechanical components of IBSSU that can move relative to one another; the platform, the bearing support arm, the shroud, and the turret. Each component is assumed to be a rigid body. In translation, the shroud and turret move with the vehicle, and the bearing support arm and the platform center of rotation are assumed to move together. The disturbance inputs are vehicle angular and translational vibrations.

The soft mount or isolator is modeled as a massless, linear spring/damper system. The coordinate axes are chosen such that they are the principal axes. It will be assumed that all axes are initially aligned and small angle approximations will be used to include cross coupling effects. Possible mass unbalance of the platform is included in the equations. This causes gravity torques to be generated and results in coupling between the angular motion and the translational motion equations.

The coordinate system for each component is chosen such that the X axis coincides with the roll axis, the Y axis coincides with the elevation (pitch) axis and the Z axis coincides with the aximuth (yaw) axis. For the Euler angles, the first rotation is an angle Φ about the roll axis. This is followed by a rotation ψ about the aximuth axis and then a rotation θ about the elevation axis.

The equations of motion for the various components are given below with the angular equations listed first:

PLATFORM:

$$\frac{d}{dt}\left[W_{px} + m_p\,(ry\,\dot{z}b - rz\,\dot{y}b)\right] = \frac{1}{J\ roll}\Big[T\ roll + B_b\,(\dot{\Phi}_b - \dot{\Phi}_p) + T_{bcf}\ \mathrm{sgn}\,(\dot{\Phi}_b - \dot{\Phi}_p) - (J_{az} - J_{el})\,Wpz\,Wpy - m_p\,g\,(ry - rz\,\Phi p)\Big]$$

$$\frac{d}{dt}\left[W_{py} + m_p\,(rz\,\dot{x}b - rx\,\dot{z}b)\right] = \frac{1}{Jel}\Big[Tel + Bb\,(\dot{\Theta}b - \dot{\Theta}p) + T_{bcf}\ \mathrm{sgn}\,(\dot{\Theta}_b - \dot{\Theta}_p) - (J\ roll - Jaz)\,W_{px}\,W_{pz} - m_{pg}\,(rx + rz\,\Theta p)\Big]$$

$$\frac{d}{dt}\left[Wpz + m_p\,(rx\,\dot{y}b - ry\,\dot{x}b)\right] = \frac{1}{J_{az}}\Big[Taz + Bb\,(\dot{\Psi}b - \dot{\Psi}p) + T_{bcf}\ \mathrm{sgn}\,(\dot{\Psi}b - \dot{\Psi}p) - (Jel - J\ roll)\,Wpy\,Wpx - mpg\,(rx\ \ \Phi p + ry\,\Theta p)\Big]$$

The rate-of-change of the Euler angles is computed using:

$$\begin{bmatrix} \dot{\Phi}\rho \\ \dot{\Theta}\rho \\ \dot{\Psi}\rho \end{bmatrix} = \begin{bmatrix} 1 & 0 & \Theta\rho \\ \Psi\rho & 1 & 0 \\ -\Theta\rho & 0 & 1 \end{bmatrix} \begin{matrix} Wpx \\ Wpy \\ Wpz \end{matrix}$$

BEARING SUPPORT ARM:

$$\frac{d}{dt}\left[W_{bx}\right] = \frac{1}{J_{bx}}\Big[Ki\,(\Phi_t - \Phi_b) + Bi\,(\dot{\Phi}_t - \dot{\Phi}_b) + B_b\,(\dot{\Phi}_p - \dot{\Phi}_b) + Tbcf\ \mathrm{sgn}\,(\dot{\Phi}_p - \dot{\Phi}_b) - (J_{bz} - J_{by})\,W_{by}\,W_{bz}\Big]$$

$$\frac{d}{dt}\left[W_{by}\right] = \frac{1}{J_{by}}\Big[Ki\,(\Theta_t - \Theta_b) + Bi(\dot{\Theta}_t - \dot{\Theta}_b) + Bb\,(\dot{\Theta}p - \dot{\Theta}b) + T_{bcf}\ \mathrm{sgn}\,(\dot{\Theta}p - \dot{\Theta}b) - (J_{bx} - J_{bz})\,W_{bz}\,W_{bx}\Big]$$

$$\frac{d}{dt}\left[W_{bz}\right] = \frac{1}{J_{bz}}\Big[Ki\,(\Psi_t - \Psi_b) + Bi\,(\dot{\Psi}_t - \dot{\Psi}_b) + B_b\,(\dot{\Psi}_p - \dot{\Psi}_b) + T_{bcf}\ \mathrm{sgn}\,(\dot{\Psi}_p - \dot{\Psi}_b) - (J_{by} - J_{bx})W_{bx}\,W_{by}\Big]$$

The rate of change of the Euler angles is computed using:

$$\begin{bmatrix} \dot{\Phi}_b \\ \dot{\Theta}_b \\ \dot{\Psi}_b \end{bmatrix} = \begin{bmatrix} 1 & 0 & \Theta_b \\ \Psi_b & 1 & 0 \\ -\Theta_b & 0 & 1 \end{bmatrix} \begin{bmatrix} W_{bx} \\ W_{by} \\ W_{bz} \end{bmatrix}$$

SHROUD:

$$\frac{d}{dt}\left[W_{sy}\right] = \frac{1}{J_{elc}}\left[T_{elm} - T_{el} + B_s(\dot{\theta}_t - \dot{\theta}_s) + Bm(\dot{\theta}_t - N^2\dot{\theta}_s) + T_{scf}\,\mathrm{sgn}(\dot{\theta}_t - \dot{\theta}_s)\right]$$

$$\begin{bmatrix}\dot{\Phi}_s\\ \dot{\theta}_s\\ \dot{\Psi}_s\end{bmatrix} = \begin{bmatrix}1 & 0 & 0\\ \Psi_s & 1 & 0\\ -\theta_s & 0 & 1\end{bmatrix}\begin{bmatrix}\dot{\Phi}_v\\ W_{sy}\\ W_{tz}\end{bmatrix}$$

TURRET:

$$\frac{d}{dt}\left[W_{tz}\right] = \frac{1}{J_{azc}}\left[Tazm - Taz + Ki(\Psi_b - \Psi_t) + Bi(\dot{\Psi}_b - \dot{\Psi}_t) + (B_t + N^2B_m)(\dot{\Psi}_v - \dot{\Psi}_t) + T_{tcf}\,\mathrm{sgn}(\dot{\Psi}_v - \dot{\Psi}_t)\right]$$

and for the Euler angles

$$\begin{bmatrix}\dot{\Phi}_t\\ \dot{\theta}_t\\ \dot{\Psi}_t\end{bmatrix} = \begin{bmatrix}1 & 0 & 0\\ -(\Psi_t - \Psi_v) & 1 & 0\\ -\theta_t & 0 & 1\end{bmatrix}\begin{bmatrix}\dot{\Phi}_v\\ \dot{\theta}_v\\ W_{tz}\end{bmatrix}$$

TRANSLATION:

$$\frac{d}{dt}\left[(m_p + m_b)\dot{x}_b + m_p(rz\,Wpy - ry\,Wpz)\right] = \frac{Ki}{d^2}(x_v - x_b) + \frac{Bi}{d^2}(\dot{x}_v - \dot{x}_b)$$

$$\frac{d}{dt}\left[(m_p + m_b)\dot{y}_b + m_p(r_x W_{pz} - r_z W_{px})\right] = \frac{Ki}{d^2}(y_v - y_b) + \frac{Bi}{d^2}(\dot{y}_v - \dot{y}_b)$$

$$\frac{d}{dt}\left[(m_p + m_b)\dot{z}_b + m_p(r_y W_{px} - r_x W_{py})\right] = \frac{Ki}{d^2}(z_v - z_b) + \frac{Bi}{d^2}(\dot{z}_v - \dot{z}_b)$$

In the angular motion equations, the terms on the right are applied torques; in the translational equations, the terms on the right are applied forces.

THE CONTROL SYSTEMS

The elevation axis and the azimuth axis control systems have the same configuration, but differ in the loop gains and compensator break points. The roll axis system operates to simply position the platform so it does not come in contact with the mechanical stops. The angular velocities of the platform are measured using rate integrating gyros aligned to sense the elevation and azimuth axes components. The elevation tachometer and resolver sense the rotation of the shroud with respect to the turret; the azimuth tachometer and resolver sense the rotation of the turret with respect to the vehicle. The sensing element in the slave loop is a 3-axis autocollimator that measures the angular position of the platform with respect to the shroud.

THE SIMULATION

The equations of angular and translational motion and the state equations for the control systems were programmed using the Advanced Continuous System Language (ACSL). The computer used is a CDC Cyber 70 series with a NOS/BE operating system.

The objective in making a simulation is to be an aid in evaluating laboratory and flight test data and in determining the sensitivity of the system to changes in the control system design. Additionally, plans are to use the program to determine performance under simulated flight conditions. The results from simulation studies, laboratory tests, and flight tests of IBSSU will be compared to an earlier stabilized platform design, the Stabilized Platform Airborne Laser (SPAL) System (4) as representing the state-of-the-art in precision stabilization performance.

In preparing the program, emphasis was in achieving a model that yields output data which closely correlates with that obtained in laboratory tests, when subjected to the same disturbances. Since the resulting motion must be quite small, it was necessary to include the effects of coupling from other axes, mass unbalance, the effect of gravity, and the coupling of the translational and angular equations. There are forty-six states in the simulation.

The validation procedures consisted of adjusting loop gains to match experimental data. The first runs were made to match the model and experimental data when subjected to test signal inputs. This is shown in Figures 6, 7, 8 for the azimuth axes. Similar curves apply for the other axes. The next step was to apply angular disturbance inputs and match the model and experimental data. This requires, as expected, some adjusting of parameters since values for friction and spring contents are not known precisely. Also, being nonlinear, the frequency response is dependent on the magnitude of the signals.

The program is such that changes in parameters and equations can be made easily. The equations for each components of IBSSU are located in a separate subroutine.

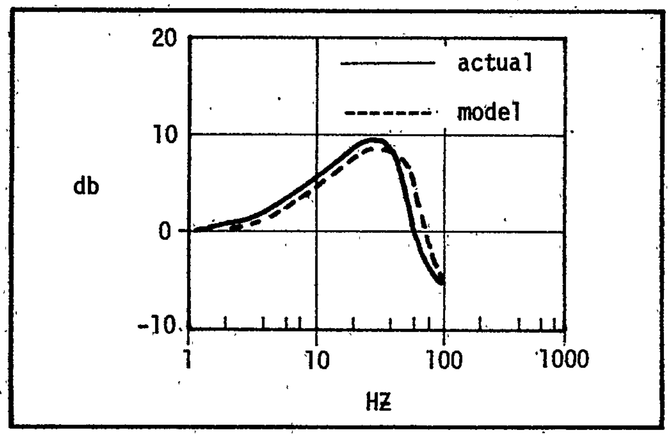

Figure 6. Azimuth Gyro Loop Frequency Response

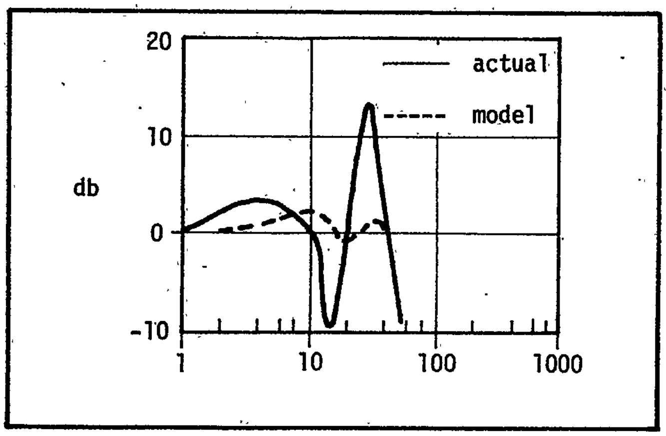

Figure 7. Azimuth Tachometer Loop Frequency Response

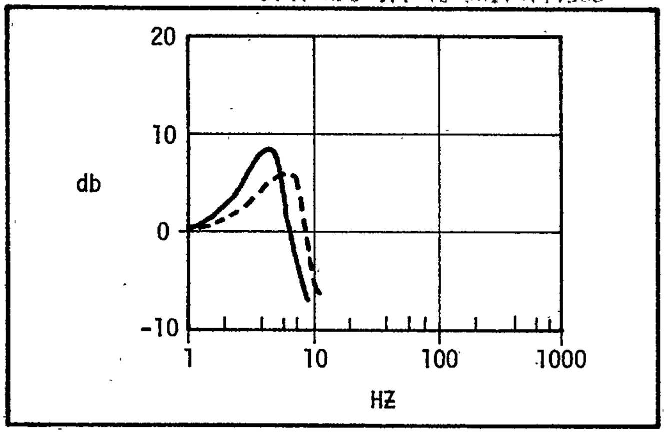

Figure 8. Azimuth Slave Loop Frequency Response

CONCLUDING REMARKS

The evaluation of IBSSU is an ongoing program. Flight tests are scheduled for the fall of 1979. The results of all the tests will be used to assess the applicability of the IBSSU concept for the Army's airborne and ground target acquisition and designation requirement.

The simulation program is being extended to take into consideration the compliance (in translation) of the payload support tube. This effect has been noticeable on other stabilized platform designs. In addition, attention is being given to a more detailed analysis of the soft-mount, one of the innovative features of this design. The possible unbalance in the spring/dampers attached to each end of the bearing support arm will be taken into account. These unbalances will result in a stronger coupling between the translational and rotational equations.

The results of the evaluation program will be compared to a previous Stabilized Platform Airborne Laser (SPAL) System (4) as representing the state-of-the-art in precision stabilization performance.

APPENDIX A

NOMENCLATURE

Bb coefficient of viscous friction, superball bearing, oz-in-sec/rad

Bi Coefficient of viscous friction, soft mount, oz-in-sec/rad

Bm coefficient of viscous friction, motor bearing, oz-in-sec/rad

Bs coefficient of viscous friction, shroud bearing, oz-in-sec/rad

B_t coefficient of viscous friction, turret, oz-in-sec/rad

d distance from center of rotation to soft-mount spring/dampers attachment point, in

g gravity, in/sec^2

J roll, Jel, Jaz platform moments of inertia, oz-in-sec^2/rad

J_{bx}, J_{by}, J_{bz} bearing support arm moments of inertia, oz-in-sec^2/rad

Jazc turret/shroud moments of inertia, oz-in-sec^2/rad

Jelc shroud moments of inertia, oz-in-sec^2/rad

Ki spring constant of soft mount, oz-in/rad

m_b mass of bearing support arm, oz-sec^2/in

m_p mass of platform, oz-sec^2/in

N gear ratio

r_x, r_y, r_z components of position vector from center of rotation to platform center of mass, in

Tbcf coulomb friction, superball bearing, oz-in

Tscf coulomb friction, shroud bearing, oz-in

Ttcf coulomb friction, turret bearing, oz-in

T roll, Tel, Taz components of wide gap actuator torques, oz-in

T elm, T azm servo motor torques, oz-in

X roll axis

Y elevation (pitch) axis

Z azimuth (yaw) axis

$\dot{x}_b$, $\dot{y}_b$, $\dot{z}_b$ translational velocity components of bearing support arm/platform center of rotation, in/sec

$\dot{x}_v$, $\dot{y}_v$, $\dot{z}_v$ translational velocity components of vehicle (helicopter), in/sec

Θ Euler angle rotation about the Y axis, rad

Φ Euler angle rotation about the X axis, rad

Ψ Euler angle rotation about the Z axis, rad

Wx, Wy, Wz components of angular velocity with respect to fixed axis, rad/sec

Subscripts:

b bearing support arm
p platform
s shroud
t turret
v vehicle

Sign function:

$$\text{sgn}\ \alpha = \begin{cases} +1 \text{ if } \alpha > o \\ 0 \text{ if } \alpha = o \\ -1 \text{ if } \alpha < o \end{cases}$$

ACKNOWLEDGMENT

John E. Tyson, Boeing Aerospace, Huntsville, Alabama implemented the equations on the computer.

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